

1.2 Equations for Fields

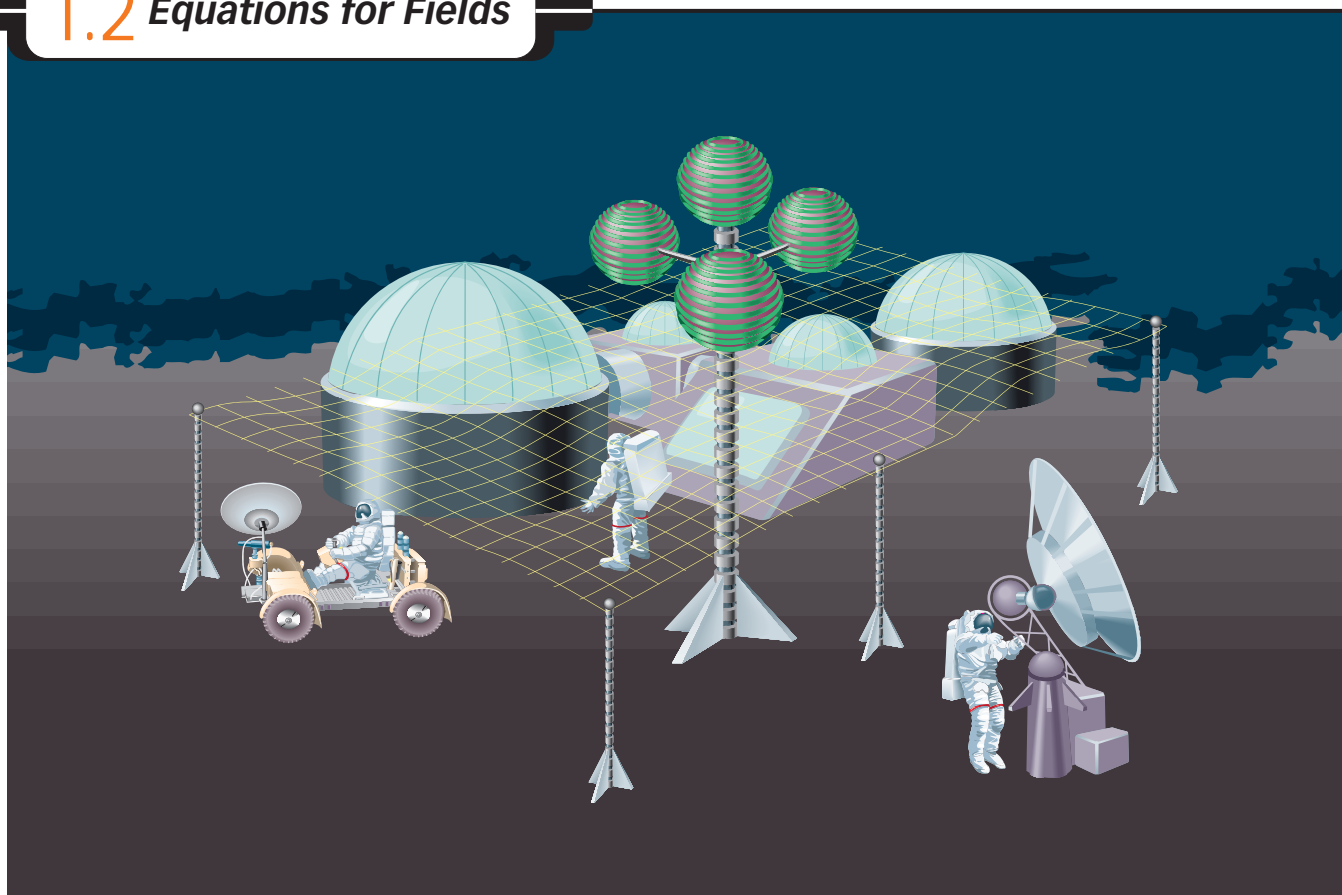
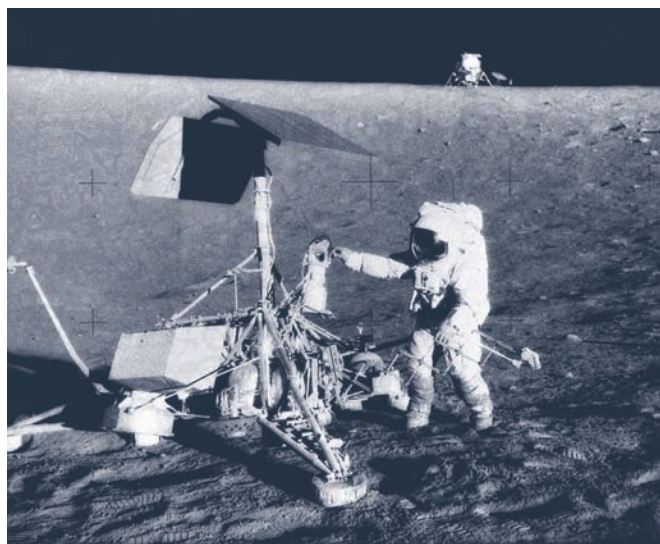


Figure C1.10: Conceptual drawing of a moon base



protons, and nuclei of helium atoms emitted from the Sun. The flow of these particles emitted from the Sun is called the **solar wind**. Larger, positively charged particles are also emitted from stars in distant parts of the galaxy. These emissions from beyond Earth's solar system are called **cosmic rays**. Long-term exposure to these types of radiation presents a real hazard to unprotected astronauts, who face an increased probability of developing cancer. When particles from the solar wind or cosmic rays collide with cells, parts of the cell may become ionized, often killing the cell. If the cell survives but segments of DNA are ionized, the cell may produce other abnormal cells that may become cancerous.

Do you think that students could one day be going to school on Mars? Could people move beyond the solar system and eventually have colonies on planets that orbit stars other than the Sun? Many scientists and engineers who have been thinking about these questions suggest the first step in exploring these possibilities would be to set up a base on the Moon. This would provide an opportunity to improve space technologies closer to Earth. A moon base could also be a convenient “stepping off point” for other space exploration.

Although people have already visited the surface of the Moon, the Apollo missions were quite short in duration. A moon base could allow people to live on the Moon for years instead of days, which is why the moon base would need a shield to protect its inhabitants from the charged space particles that bombard the lunar surface. Some of these particles are electrons,

▶ **solar wind:** a stream of high-speed, ionized particles ejected from the Sun, consisting mainly of electrons, protons, and helium nuclei

▶ **cosmic rays:** a stream of high-speed, ionized particles ejected from the objects beyond the solar system, consisting mainly of atomic nuclei

How would the large spheres in Figure C1.10 protect astronauts from the solar wind and cosmic rays? If Earth is a giant spaceship travelling rapidly around the Sun, it is exposed to these radiations as well. How are you protected from these hazards? What do fields have to do with the answers to these questions and with space exploration in general? You will have an opportunity to answer these questions in this lesson.

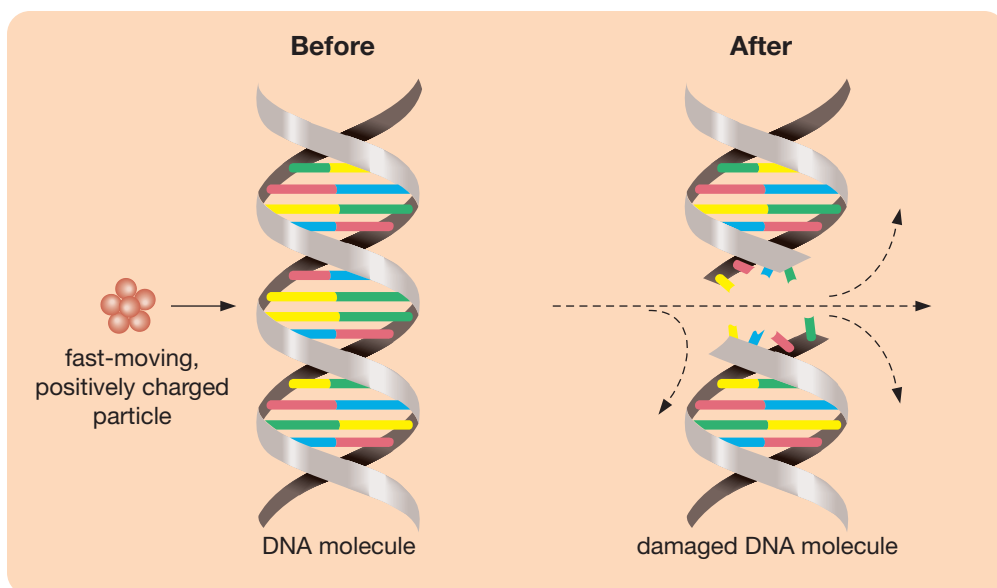


Figure C1.11: The high-energy, positively charged particles from cosmic rays have the potential to break both strands in a DNA molecule during a collision. This kind of damage is more difficult for a cell to repair than a single-strand break.

Practice

9. In general terms, explain how the presence of a positively charged particle could cause the ionization of other molecules, leading to the breakage of chemical bonds.
10. Explain why it is more difficult for cells to repair damage to DNA molecules if both DNA strands have been affected.

Gravitational Field Strength

Before considering the design of space stations, it is necessary to deal first with the challenges of leaving the surface of Earth. Think back to the last time you climbed a number of stairs. Each step required you to exert a force to overcome the natural tendency of Earth's gravitational field to pull you back down to the surface. With a space-shuttle launch, the rocket engines not only supply the force to overcome the force of gravity, they also accelerate the shuttle and its contents to high speeds—about 8 km/s for low-Earth orbit. It is the combination of high speed and gravitational field that defines a stable orbit. Without these high speeds, satellites would be pulled back to Earth by the planet's gravitational field.



In order to calculate the speed necessary for a satellite to maintain a certain orbit, and to determine the amount of rocket fuel required to achieve that orbit, an equation is needed to predict the **gravitational field strength**.

$$g = \frac{Gm}{r^2}$$

Labels for the equation:

- G : gravitational constant, $6.67 \times 10^{-11} \text{ N}\cdot\text{m}^2/\text{kg}^2$
- m : mass of source (kg)
- g : gravitational field strength (N/kg)
- r : distance from centre of source (m)

Note that the key variables on the right side of the equation are m , the mass of the object that is the source of the field, and r , the distance from the centre of the source. The gravitational constant, G , is not a variable—its value, $6.67 \times 10^{-11} \text{ N}\cdot\text{m}^2/\text{kg}^2$, never changes. The gravitational constant is needed to ensure that when the value for source mass is entered in kilograms and the value for distance is entered in metres, the result of the calculation will give the correct value for gravitational field strength in newtons per kilogram.

gravitational field strength: the number of newtons per kilogram a test body will experience at a given location from a source mass

The units of gravitational field strength reveal an important feature of this quantity. Multiplying the mass of a test body by the gravitational field strength gives the **gravitational force** that acts on that test body.

$$F_g = mg$$

gravitational force → F_g mass of a test body → m gravitational field strength → g

Units: $\text{N} = (\text{kg}) \left(\frac{\text{N}}{\text{kg}} \right)$

Example Problem 1.4 illustrates how these ideas can be applied.

► **gravitational force:** the force exerted on a test body by a gravitational field; calculated by multiplying the mass of the test body by the gravitational field strength

Example Problem 1.4

Earth's radius has an average value of $6.37 \times 10^6 \text{ m}$, while Earth's mass has a value of $5.98 \times 10^{24} \text{ kg}$.

- Calculate the value of the gravitational field strength at Earth's surface.
- A person with a heavy backpack has a mass of 100 kg and can be considered a test body for the gravitational field. Use the value from part a. to predict the force of gravity Earth would exert on this person.



continued

Solution

a. $r = 6.37 \times 10^6 \text{ m}$

$$m_{\text{source}} = 5.98 \times 10^{24} \text{ kg}$$

$$g = ?$$

$$g = \frac{Gm_{\text{source}}}{r^2} = \frac{(6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2)(5.98 \times 10^{24} \text{ kg})}{(6.37 \times 10^6 \text{ m})^2}$$

$$= 9.829\,878\,576 \text{ N/kg}$$

$$= 9.83 \text{ N/kg}$$

The strength of the gravitational field at Earth's surface is 9.83 N/kg.

Note: The following keystrokes summarize a typical entry for many calculators:

(	6.67	2nd	[EE]	(-)	11)
x	(	5.98	2nd	[EE]	24)
÷	(	6.37	2nd	[EE]	6)
x ²	ENTER					

Consult your calculator owner's manual for more information.

b. $g = 9.829\,878\,576 \text{ N/kg}$

$$m_{\text{test}} = 100 \text{ kg}$$

$$F_g = ?$$

$$F_g = m_{\text{test}} g = (100 \text{ kg})(9.829\,878\,576 \text{ N/kg}) = 983 \text{ N}$$

Using the value from part a., Earth's gravitational field will exert a force of 983 N on the person with the backpack.

Note: The unrounded value for g is used as an input in part b., but the final answer is recorded to three significant digits, consistent with the given values.

The calculation in part b. of Example Problem 1.4 reveals an important aspect of gravitational field strength: it provides a convenient way to predict the amount of force a test body would experience in the field. The only caution is not to mix up gravitational field strength with gravitational force. Many students use units to help keep this clear.

- Force of gravity is measured in newtons (N).
- Gravitational field strength is measured in newtons per kilogram (N/kg).

The value calculated in part a. of Example Problem 1.4 is based on the average value for the radius of Earth and ignores the effects of Earth's spin. So, it follows that the gravitational field strength is also an average value for Earth. In Alberta, the gravitational field strength is 9.81 N/kg. Does this number look familiar? In previous courses you used 9.81 m/s² as the value for acceleration due to gravity. As the following analysis of units reveals, this is not a coincidence—the units for acceleration due to gravity and gravitational field strength are equal. The value for the gravitational field strength of Earth varies from a low of 9.79 N/kg at the equator to a high of 9.83 N/kg at the poles. This variation is due to Earth's spin and to the flattening of Earth at its poles.

This new interpretation of the value of g helps to answer some important questions that may not have been answered in previous courses, such as why does the Moon's surface have a different value for the acceleration due to gravity than the surface of Earth does? Example Problem 1.5 provides insight into the answer to this question.

$$\begin{array}{c}
 9.81 \frac{\text{N}}{\text{kg}} \\
 \downarrow \\
 9.81 \frac{\cancel{\text{kg}} \cdot \text{m/s}^2}{\cancel{\text{kg}}} \\
 \downarrow \\
 9.81 \text{ m/s}^2
 \end{array}$$

Example Problem 1.5

The Moon has an average radius of 1.74×10^3 km and a mass of 7.35×10^{22} kg.

- Calculate the gravitational field strength of the Moon.
- Explain why the Moon has a different value for gravitational field strength than Earth does.
- An astronaut in a new lightweight spacesuit has a mass of 100 kg and could be considered a test body for the gravitational field of the Moon. Determine the force of gravity exerted on the astronaut by the Moon's gravitational field.

Solution

a. $r = 1.74 \times 10^3 \text{ km} \times \frac{1000 \text{ m}}{1 \text{ km}}$ **Note: Kilometres are converted to metres before the values are substituted in the equation.**

$$= 1.74 \times 10^6 \text{ m}$$

$$m_{\text{source}} = 7.35 \times 10^{22} \text{ kg}$$

$$g = ?$$

$$\begin{aligned}
 g &= \frac{Gm_{\text{source}}}{r^2} \\
 &= \frac{(6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2)(7.35 \times 10^{22} \text{ kg})}{(1.74 \times 10^6 \text{ m})^2} \\
 &= 1.619\,252\,874 \text{ N/kg} \\
 &= 1.62 \text{ N/kg}
 \end{aligned}$$

The strength of the gravitational field at the Moon's surface is 1.62 N/kg.

- Gravitational field strength depends upon two key variables: m , the mass of the source, and r , the distance from the centre of the source. Since both of these values are significantly different from the values for Earth, the Moon has a different value for gravitational field strength.

c. $g = 1.619\,252\,874 \text{ N/kg}$

$$m_{\text{test}} = 100 \text{ kg}$$

$$F_g = ?$$

$$\begin{aligned}
 F_g &= m_{\text{test}} g \\
 &= (100 \text{ kg})(1.619\,252\,874 \text{ N/kg}) \\
 &= 162 \text{ N}
 \end{aligned}$$

Using the value from part a., the Moon's gravitational field will exert a force of 162 N on the astronaut.



Compare the solution to part b. of Example Problem 1.4 to the solution to part c. of Example Problem 1.5. The mass of the test body was the same in both cases (100 kg), but the force of gravity was different. How would you explain this? Look at the values of gravitational field strength in both locations. Even though the masses of the test bodies were the same, the differences in gravitational field strength resulted in different forces.

Utilizing Technology

Plotting the Gravitational Field Strength of Venus

Purpose

You will use a graphing calculator to calculate, graph, and identify trends in gravitational field strength values for Venus.

Background Information

Due to similar values for mass and radius, it was once thought that Venus was very similar to Earth. Early astronomers referred to Venus and Earth as “sister planets.” However, the conditions on the surface of Venus are dramatically different from those on Earth.

Venus’s atmosphere is so thick with carbon dioxide that the “greenhouse effect” makes the surface temperatures as hot as an oven on “self-clean”: 482°C. Figure C1.12 shows the thick clouds of sulfuric acid drops that blanket Venus. The photograph was taken by a probe that was sent to explore Venus in 1979.



Figure C1.13: *Venus Express*



Science Skills

- ✓ Performing and Recording
- ✓ Analyzing and Interpreting

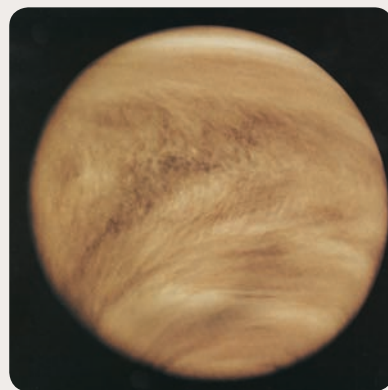


Figure C1.12: Venus

More recent exploration of Venus began in 2006 with the European Space Agency’s probe, *Venus Express*. The orbit of this probe will be modified over the course of the mission, depending upon the data that needs to be collected. Planning for a stable orbit means that both the speed of the probe and the strength of the gravitational field at various locations around Venus will have to be determined.

Materials

- graphing calculator
- “Plotting the Gravitational Field Strength of Venus” handout

Procedure

Obtain the “Plotting the Gravitational Field Strength of Venus” handout from the Science 30 Textbook CD. Follow the steps described in the handout.



1. Plot a graph of your results in the space provided in the handout. Draw a smooth curve to connect the data points.

Analysis

2. Compare the data for trial 5 with the data for trial 1.

- a. How does the distance value for trial 5 compare to the distance value for trial 1?

Answer by completing this sentence:

To get the distance for trial 5, multiply the distance value for trial 1 by _____.

- b. How does the gravitational field strength value for trial 5 compare to the gravitational field strength for trial 1?

Answer by completing this sentence:

To get the gravitational field strength for trial 5, multiply the gravitational field strength for trial 1 by the decimal _____ (rounded to three digits) or by the fraction _____.

3. Repeat the analysis of question 2 for the values in trials 2 and 7.
4. Repeat the analysis of question 2 for the values in trials 3 and 9.
5. Describe the pattern that emerges from your answers to questions 2, 3, and 4.
6. Use the equation for gravitational field strength to explain the pattern that you identified in your answer to question 5.

The Effect of $\frac{1}{r^2}$ on Gravitational Field Strength

The position of r in the denominator of the gravitational field strength equation means that as distance from the source increases, the value of gravitational field strength decreases. This trend is compounded by the fact that the value of r is squared. Figure C1.14 shows how these ideas apply to the gravitational field of Mercury, one of the smaller planets in the solar system.

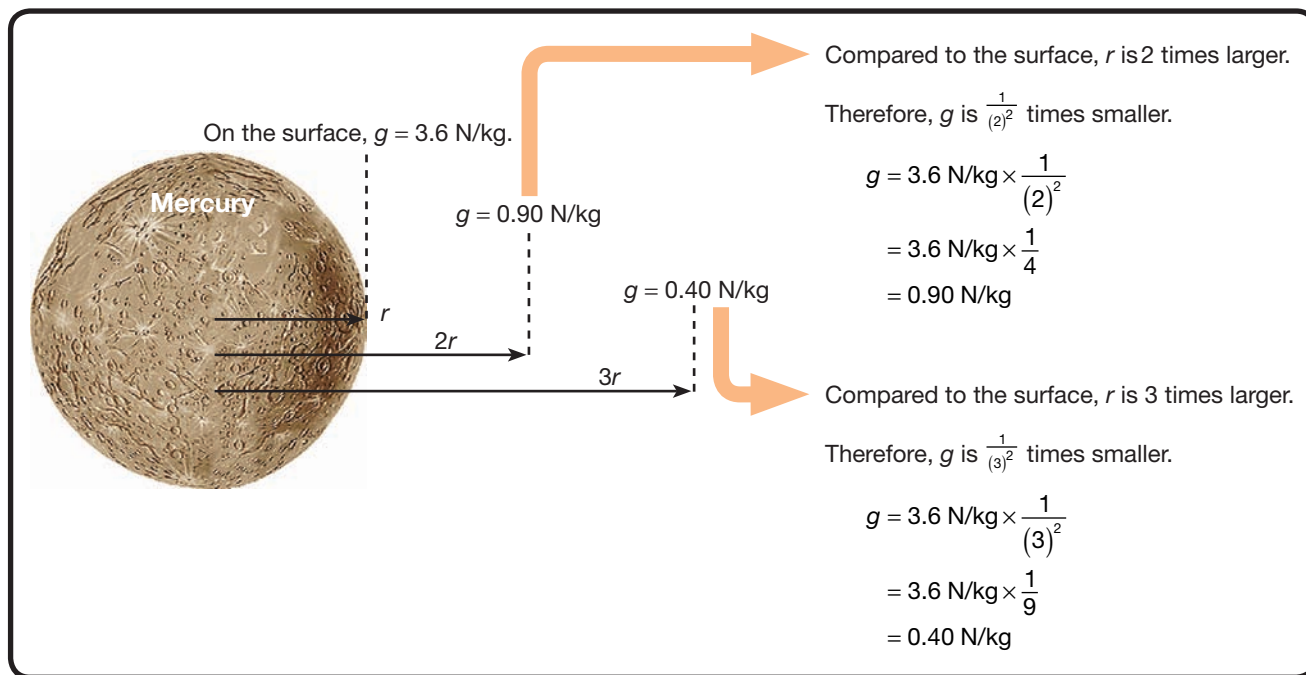


Figure C1.14

Students who like mathematics find that the patterns shown in Figure C1.14 are a convenient shortcut that reduces the need for always doing long calculations. For example, given the information in Figure C1.14, how strong would the gravitational field strength be at a location ten times farther away than the surface of Mercury? Since the distance is ten times farther away, the gravitational field strength should be $\frac{1}{(10)^2}$ or $\frac{1}{100}$ times larger, or 0.036 N/kg .

Practice

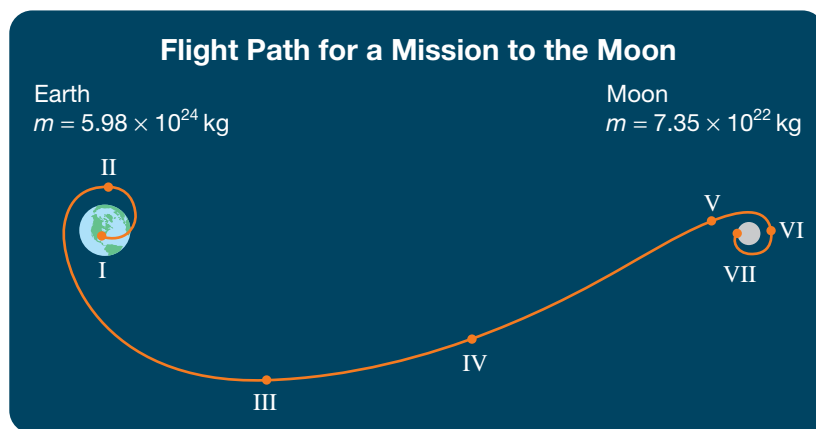
11. Before you begin solving problems, it is a good idea to review how to enter these calculations into your calculator. Enter the data for part a. of Example Problem 1.4 and part a. of Example Problem 1.5 into your calculator and confirm the answers. A common data-entry error is forgetting to square the value for distance, r . Would this error generate gravitational field strength values that are too large or too small?



Practice

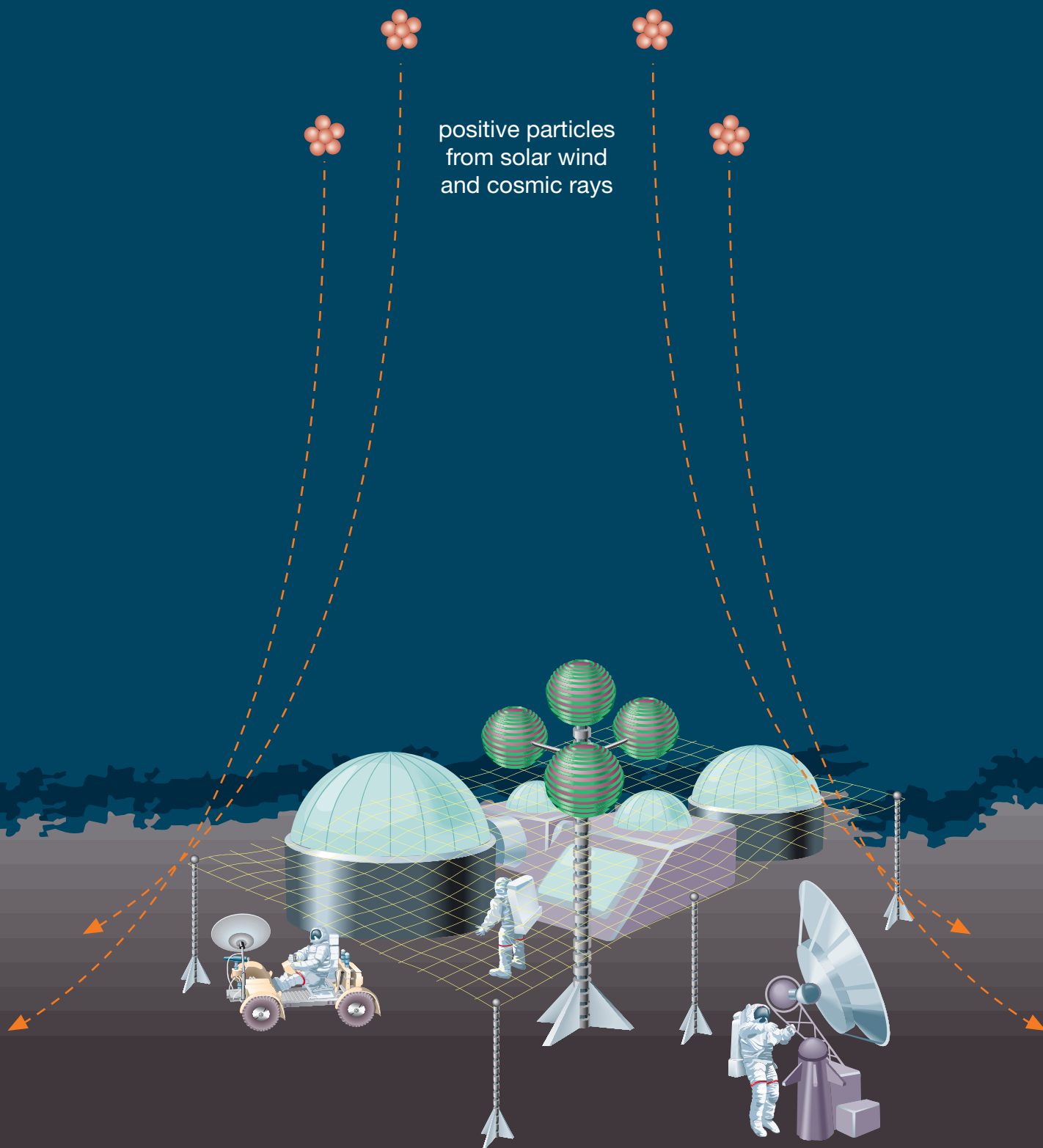
Use the following information to answer questions 12 to 15.

The following illustration shows a typical path for a space vehicle on a mission to the Moon.



Location	Description	Distance from Centre of Earth (m)	Distance from Centre of Moon (m)
I	launch site on Earth	6.37×10^6	
II	high-Earth orbit	2.00×10^7	
III	about $\frac{1}{4}$ of distance to Moon	1.00×10^8	
IV	about $\frac{1}{2}$ of distance to Moon	2.00×10^8	
V	point of equal gravitational attraction	3.457×10^8	3.83×10^7
VI	low-Moon orbit		1.84×10^6
VII	landing site on Moon		1.74×10^6

12. Calculate the gravitational field strength of Earth at locations II, III, IV, and V.
13. Calculate the gravitational field strength of the Moon at locations V and VI.
14. Refer to the values you calculated for gravitational field strength at location V in questions 12 and 13. One of these values is the gravitational field strength of Earth. The other is the gravitational field strength of the Moon.
 - a. Sketch a diagram of Earth and the Moon with location V indicated.
 - b. Add an arrow to your diagram to indicate the size and direction of the gravitational field of Earth at location V.
 - c. Add an arrow to your diagram to indicate the size and direction of the gravitational field of the Moon at location V.
 - d. Explain why location V is referred to as the point of equal gravitational attraction.
 - e. If a space vehicle comes to rest and turns off its engines at location V, it will not accelerate toward the Moon or Earth. Explain why.
15. Note the following observations in your answers to question 12:
 - observation 1: Location IV is two times farther from Earth than location III, and the gravitational field strength at location IV is $\frac{1}{4}$ the gravitational field strength at location III.
 - observation 2: Location IV is ten times farther from Earth than location II, and the gravitational field strength at location IV is $\frac{1}{100}$ the gravitational field strength at location II.
 - a. Use the equation for gravitational field strength to explain observation 1.
 - b. Use the equation for gravitational field strength to explain observation 2.



positive particles
from solar wind
and cosmic rays

Electric Field Strength

At the beginning of this lesson, it was explained that the large spheres in the illustration of the space station help to protect astronauts from ionizing effects of charged particles in the solar wind and in cosmic rays. The spheres are able to deflect these particles away from the space station by generating strong electric fields. To ensure that the electric fields are sufficient to protect the people working below, an equation is needed to predict the **electric field strength**.

electric field strength: the number of newtons per coulomb that a test body will experience at a given location from a source charge

The equation for electric field strength is very similar in structure to the equation for gravitational field strength.

$$|\vec{E}| = \frac{kq}{r^2}$$

electric field strength (N/C) coulomb constant $8.99 \times 10^9 \text{ N}\cdot\text{m}^2/\text{C}^2$
 distance from centre of source charge on source (C)

Just like the equation for gravitational field strength, this equation involves a constant to ensure that the equation works for the given units. In this case, the coulomb constant is a large value: $k = 8.99 \times 10^9 \text{ N}\cdot\text{m}^2/\text{C}^2$. This is because, overall, electric forces and fields are more significant than gravitational fields. Gravitational effects are only noticeable when one of the objects happens to have the mass of a planet, a moon, or a star. Electrical effects, on the other hand, can be observed among very ordinary objects.

Another unique feature of this equation is the notation. The symbol for the vector electric field is \vec{E} . Since this equation is just for the magnitude or strength of the electric field, it might be tempting to simply drop the vector arrow and use E , but this is already used as the symbol for energy. So, the absolute value signs were added to the vector electric field symbol, indicating that direction is not involved in this equation—it only describes the strength of the electric field.

The equation for electric field strength is an important tool for the NASA engineers who are drafting early plans for the protective spheres on the moon base. Each sphere has to be highly charged in order to generate a field that can exert forces on harmful particles from the solar wind and cosmic rays.

Example Problem 1.6 illustrates how the equation for electric field strength is applied to this situation. As was the case for solving gravitation problems, you have to be careful not to confuse the force with the field that exerts the force. Again, many students find that units help to keep them from getting mixed up:

electric force: the force exerted on a charged test body by an electric field; calculated by multiplying the electric field strength by the charge on the test body

- **Electric force** is measured in newtons (N).
- Electric field is measured in newtons per coulomb (N/C).
- Multiplying the electric field by the charge on a test body indicates the electric force on that test body.

$$\text{Units: } \text{N} = \left(\frac{\text{N}}{\text{C}} \right) (\text{C})$$

electric force

Equation: $F_e = |\vec{E}|q$

electric field strength charge on a test body

Example Problem 1.6

One of the charged spheres being developed to protect a base on the Moon has a charge of $+0.0200 \text{ C}$.

- Determine the strength of the electric field 20.0 m from the centre of this sphere.
- The centre of one sphere is about 20.0 m from the next. Consider a second sphere that is also charged at $+0.0200 \text{ C}$ to be a test body for the first sphere. Calculate the force the electric field of the first sphere will exert on the second sphere.
- Consider your answer to part b. Explain the implications of this answer for the designers and engineers at NASA.

Solution

a. $q_{\text{source}} = +0.0200 \text{ C}$

$r = 20.0 \text{ m}$

$|\vec{E}| = ?$

$$|\vec{E}| = \frac{kq_{\text{source}}}{r^2} = \frac{(8.99 \times 10^9 \text{ N}\cdot\text{m}^2/\text{C}^2)(0.0200 \text{ C})}{(20.0 \text{ m})^2} = 449\,500 \text{ N/C} = 4.50 \times 10^5 \text{ N/C}$$

The electric field 20.0 m away from the sphere would be $4.50 \times 10^5 \text{ N/C}$.

b. $q_{\text{test}} = +0.0200 \text{ C}$

$|\vec{E}| = 449\,500 \text{ N/C}$

$F_e = ?$

$$F_e = |\vec{E}|q_{\text{test}} = (449\,500 \text{ N/C})(0.0200 \text{ C}) = 8.99 \times 10^3 \text{ N}$$

The force exerted by the electric field of the first sphere on the second sphere is $8.99 \times 10^3 \text{ N}$.

- The forces the spheres exert on each other would have to be balanced by the forces of the structure that holds them together. Since these forces are large, the supports holding the spheres together would have to be strong enough to hold the entire structure together.

Example Problem 1.6 illustrates how large the electric field would be around the charged spheres. It also illustrates a key challenge for the engineers—since each sphere would generate an electric field that would exert a large repulsive force on the others, the spheres would have to be well-supported. Given this challenge, you might wonder why it's not possible to use one large sphere instead of a cluster of smaller ones. The thinking here is that the electric fields of the smaller spheres would overlap, creating one very large electric field to repel the incoming positive particles.

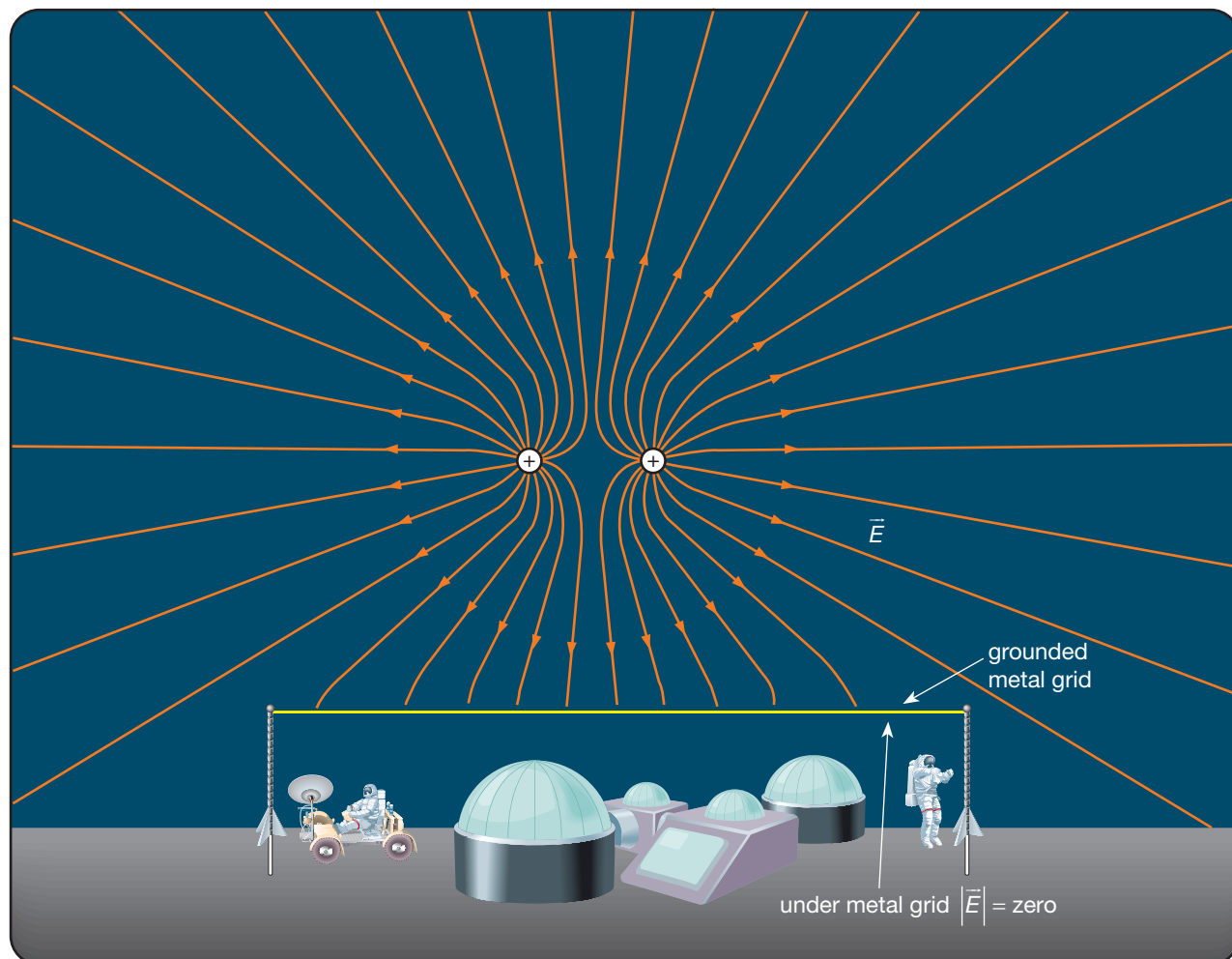


Figure C1.15

NASA estimates over 100 million volts will be required to maintain a field this strong above the lunar base. Clearly, the structures supporting the spheres would have to be made from non-conducting material. Recalling what you learned about lightning in Lesson 1.1, consider how hazardous it is for humans to work in an environment where there are large amounts of charge separated at high voltages. The metal grid above the base would be **grounded**, providing a safe conducting path for any stray or excess charges to flow to the ground below. The metal grid would also shield the people at the base from the strong electric fields, since the electric field strength is zero below the grid.

▶ **grounded:** connected to the ground; providing a safe conducting path for stray or excess charges; having zero electric potential energy

Practice

16. Refer to Figure C1.15, which shows the two charged spheres above the lunar base. The distance between the centres of the spheres is 20.0 m, and each sphere has a charge of +0.0200 C. There is a point midway between the spheres, the midpoint, that is exactly 10.0 m from the centre of each sphere.
- Calculate the electric field strength at the midpoint due to the sphere on the left.
 - Determine the direction of the electric field at the midpoint due to the sphere on the left.
 - Use your answers to questions 16.a. and 16.b. to determine the strength and direction of the electric field at the midpoint due to the sphere on the right.
 - Explain why the sum of the electric fields at the midpoint is zero.

Electric Fields and You



Figure C1.16

Whether you are pulling clothes out of the dryer or combing your hair with a plastic comb on a dry day, you encounter the effects of electric fields on a daily basis. A simple demonstration of electric fields involves rubbing a balloon through your hair on a dry winter day. As each individual hair loses electrons to the balloon, the balloon acquires a negative charge and the individual hairs become positive test bodies. As shown in Figure C1.16, the positive test bodies respond to the electric field of the negatively charged balloon. In these circumstances, the balloon probably picks up only a few nanocoulombs of charge, but the electric field strength can still be determined.

Example Problem 1.7

A balloon is given a charge of -4.5 nC .

- Determine the electric field strength 30 cm from the centre of the balloon.
- Sketch a diagram of the electric field lines around the balloon.

Solution

$$\begin{aligned} \text{a. } q_{\text{source}} &= -4.5 \text{ nC} \\ &= -4.5 \times 10^{-9} \text{ C} \end{aligned}$$

$$\begin{aligned} d &= 30 \text{ cm} \times \frac{1 \text{ m}}{100 \text{ cm}} \\ &= 0.30 \text{ m} \end{aligned}$$

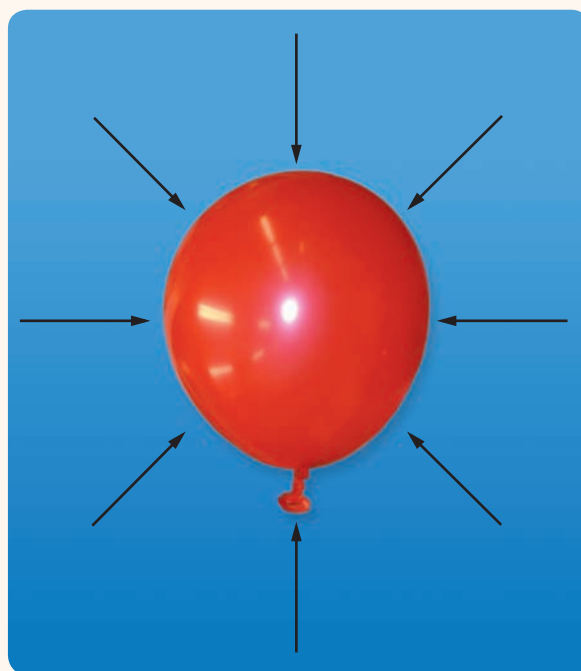
$$|\vec{E}| = ?$$

$$\begin{aligned} |\vec{E}| &= \frac{kq_{\text{source}}}{r^2} \\ &= \frac{(8.99 \times 10^9 \text{ N}\cdot\text{m}^2/\text{C}^2)(4.5 \times 10^{-9} \text{ C})}{(0.30 \text{ m})^2} \\ &= 4.5 \times 10^2 \text{ N/C} \end{aligned}$$

The negative sign is not used in the equation. The negative sign is used to determine direction in part b.

The electric field strength 30 cm from the balloon's centre is $4.5 \times 10^2 \text{ N/C}$.

- Since the direction of the electric field is determined by the force on a positive test body, the electric field lines are directed toward the negatively charged balloon.



Practice

17. Figure C1.17 shows the set-up of a demonstration you can try in a very dry room. Given how dry it is inside most buildings in Alberta in the winter, this demonstration works best if it is done in December, January, or February.

- Sketch a diagram showing the two balloons and the electric fields around them.
- Assume each balloon has a charge of -5.0 nC . If the distance between the centres of the balloons is 44 cm , the midpoint is 22 cm from the centre of each balloon. Perform the necessary calculations and analysis to demonstrate that the electric field strength is zero at the midpoint.

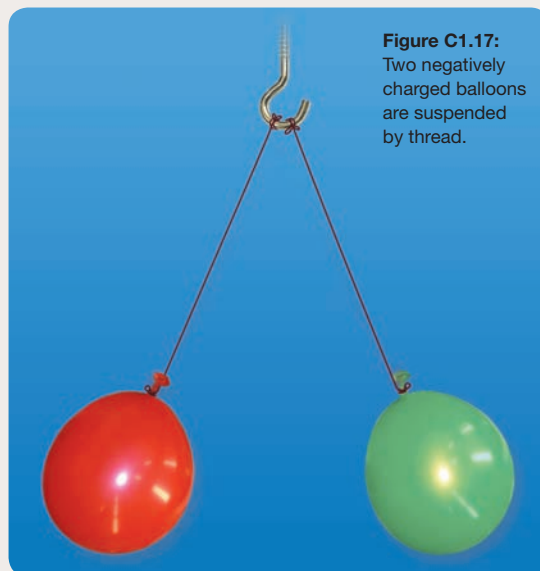


Figure C1.17: Two negatively charged balloons are suspended by thread.



DID YOU KNOW?

When working with computer circuit boards, it is important to ensure they are properly grounded. A grounding wire connected to your wrist allows stray amounts of charge that may accumulate on your body to be conducted to the ground instead of passing through sensitive electronic components. The charge accumulated on your body by simply walking across a room could be enough to seriously damage a new sound card for a computer. Warning labels remind you to ground yourself before handling sensitive components.



Moving Charges and Magnetic Fields

In considering NASA's plans for a moon base, you saw how an arrangement of positively charged spheres can protect the base from the bombardment of positively charged particles that are key components of cosmic rays and the solar wind. The solar wind also contains negatively charged particles—high-speed electrons. Since this form of radiation also has the ability to ionize matter, the high-speed electrons represent a health hazard to the astronauts working at the base. Given that the positively charged spheres would exert forces to attract these high-speed electrons toward the base, there would need to be another component of the design to deflect these particles as well as the positively charged particles from cosmic rays and the solar wind.

NASA's plans call for the positively charged spheres to be partially wrapped in insulating wire carrying a large **electric current**. The flow of moving charges through the coils of wire would exert a force on the incoming electrons before they reached the base, so a field must be involved. What kind of field is produced by the electric current? Can this effect be demonstrated here on Earth? You will have a chance to answer these questions in the next investigation.

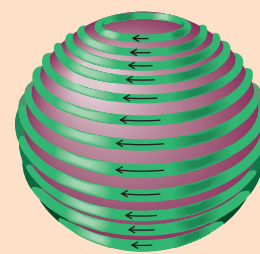


Figure C1.18: Insulated wires carrying an electric current surround the positively charged sphere.

electric current: the flow of electric charge from one point to another

Investigation

Using a Coil to Deflect an Electron Beam



Science Skills

- ✓ Performing and Recording
- ✓ Analyzing and Interpreting
- ✓ Communication and Teamwork

Purpose

You will build a small coil and then pass a current through the coil for a few seconds at a time. At the moments when the current is passing through the coil, you will observe the effects the current has on a compass needle and on a beam of electrons.

Materials

- 1 cardboard cylinder, about 4 cm in diameter and 10 cm in length (empty toilet-tissue roll)
- 10 m of 26- or 28-gauge enamelled magnet wire
- 4 AA cells in a plastic battery pack
- 2 test leads with alligator clips at each end
- access to an operating CRT monitor (conventional TV or computer monitor)
- small knife or 1 piece of fine sandpaper
- tape
- compass
- “Magnetic Field Surrounding a Small Coil” handout



CAUTION!

This investigation involves briefly passing a current through a coil. The coil will become warm and remain that way for a few seconds after the current has passed. If the coil is left connected for more than a few seconds, it will become uncomfortably warm and will unnecessarily drain the batteries. Allow the current to pass through the coil for only a few seconds at a time.

Part A: The Magnetic Field Lines Around a Current-Carrying Coil

Procedure and Observations

step 1: Wrap 10 m of enamelled magnet wire around the cardboard cylinder to make a small coil. Leave about 10 cm of wire free at each end of the coil to act as contacts. Use adhesive tape to hold the contacts and coils in place. Use a small knife or sandpaper to carefully scrape the enamel coating from the last 5 cm of each contact, as shown in Figure C1.19.

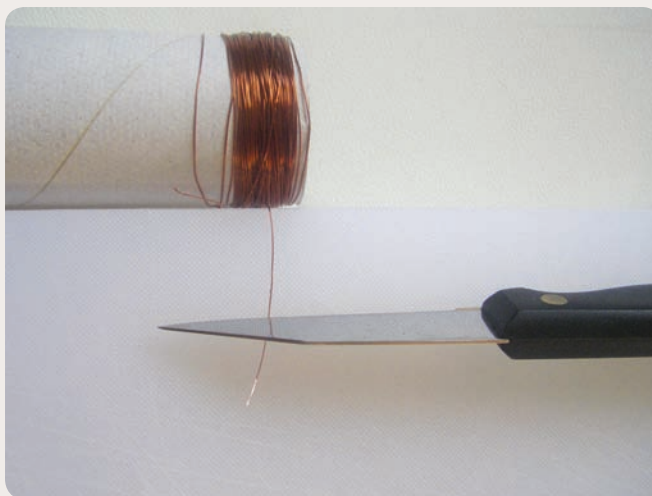


Figure C1.19

step 2: Obtain the “Magnetic Field Surrounding a Small Coil” handout from the Science 30 Textbook CD. Without connecting the coil to the AA cells, arrange the equipment as shown in the handout. Adjust the position of the coil so its axis is aligned in the east-west direction.



step 3: Carefully connect one of the coil’s contacts to the AA cells with a test lead. While watching the north end of the compass needle, make a brief connection between the coil’s other contact and the AA cells. Break the connection as soon as you can tell which way the compass needle is pointing when the current is flowing. Record which way the north end of the compass needle pointed for the corresponding compass position on the handout.

step 4: Repeat step 3 with the compass in each of the other positions indicated on the handout. Record your observations on the handout.

Analysis

1. On the handout, connect the arrows you drew to show the compass needle’s directions to create a magnetic field-line diagram. Identify another situation where you have seen a pattern of magnetic field lines like the one produced by the coil.
2. Compare your results to those of several other groups of students.
 - a. Identify the common feature of the results from all groups.
 - b. How do you account for the two possible different outcomes?

Part B: Observing the Deflection of an Electron Beam

Background Information

Conventional televisions and old computer monitors produce an image by shooting beams of electrons toward the screen from the back. The inside of the screen consists of thin stripes of three different phosphor compounds. One glows red when electrons strike it, the second glows green, and the third glows blue. Each thin phosphor stripe is targeted by one of the three electron beams.

If you look very closely at a TV screen, you should be able to see the light emitted by the tiny red, green, and blue bars. To ensure the TV picture has accurate colours, each electron beam is aimed to precisely hit the bar of the proper colour. In the next part of this investigation, you will carefully examine the effects of the magnetic field produced by your coil on the ability of the electrons to strike the correct phosphor stripe.

- step 1:** Turn on the TV and switch to a channel that has stationary (still) vertical lines dividing areas that have different colours. If you have cable television, the channel that displays the list of programs works well.
- step 2:** Without connecting the coil to the AA cells, arrange the equipment as shown in Figure C1.20.
- step 3:** Connect one end of the coil to the AA cells. Look across the top of the coil at the TV screen to find a tiny area of phosphor stripes on the boundary between the two regions of colour. While carefully observing the boundary between the phosphor stripes, make a very brief connection between the other contact and the AA cells. Observe which way the colours seemed to shift on the screen. Was it to the right or to the left? Make and break the connection several times until you can tell which way the colours seem to shift when the current flows in the coil. Record your results.
- step 4:** Reverse the connections of the coil to the AA cells and repeat step 3. Record your results.

Analysis

3. The tiny stripes of phosphor are unable to move because they are bonded to the inside of the TV screen. Using the information in the background information, how do you account for the observed shift in the colours in step 3?
4. Many speakers are built with powerful magnets. Based upon what you have observed in this investigation, suggest a reason why speakers that are built for use with televisions that utilize electron beams are magnetically shielded.
5. Conventional televisions are very heavy for several reasons, but one reason is that the glass used in their screens contains 2 kg to 4 kg of lead. Explain why it is important to send electronic components, like televisions and old computer monitors, to specialized electronics recycling centres instead of to landfills.

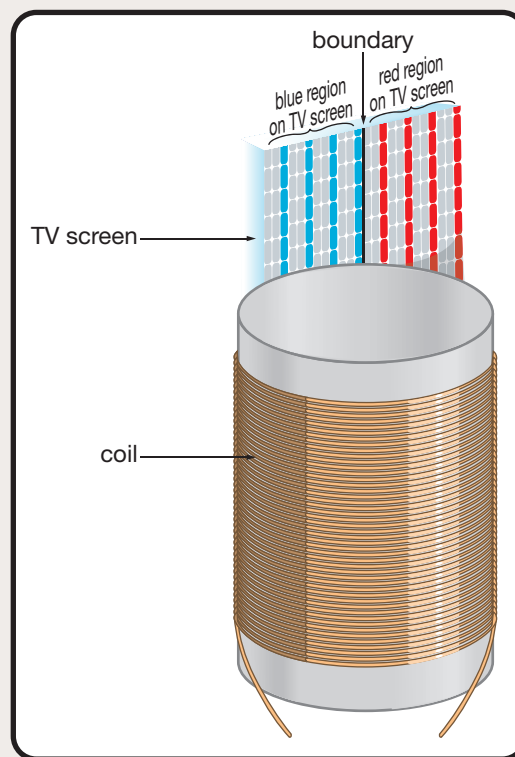
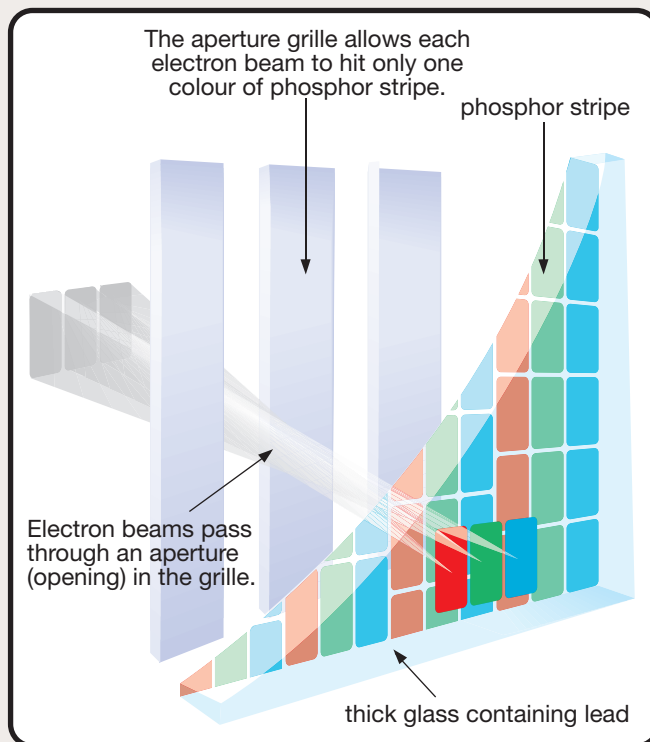


Figure C1.20: Holding the coil close to the TV screen causes the colours in the picture to shift.

Moving Charges Generate All Magnetic Fields

As shown in Figure C1.21, an electric current passing through a coil of wire can generate a magnetic field with the same shape as the magnetic field around a bar magnet. Note that the symbol for a magnetic field is \vec{B} . Since the magnetic field at one end of the coil attracts the north end of a compass needle and the other end repels it, the ends of the coil can be labelled north and south. You might be surprised to know that this is not a coincidence because the magnetic field produced by a bar magnet is also due to electric currents.

Figure C1.22 shows that electrons within atoms are in constant motion—each electron orbits the nucleus of the atom and also spins like a top on its own axis. Since electrons are charged and since both of these motions involve a moving charge, both the orbital motion and the spinning motion can be considered to be an electric current flowing in a loop. So, why aren't all materials magnetic? In most substances, the orbits and spinning of the electrons do not align, so the magnetic fields that are produced cancel themselves out. In substances like iron, cobalt, and nickel, it is possible to align the atoms so that the magnetic fields generated by the spinning and orbiting electrons reinforce one another. The result is a permanent magnet.

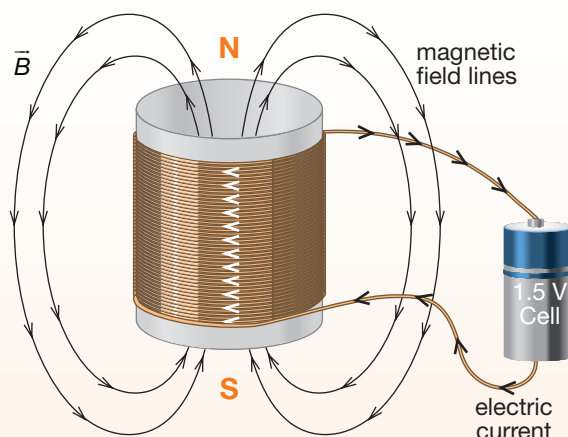


Figure C1.21: An electric current can generate a magnetic field.

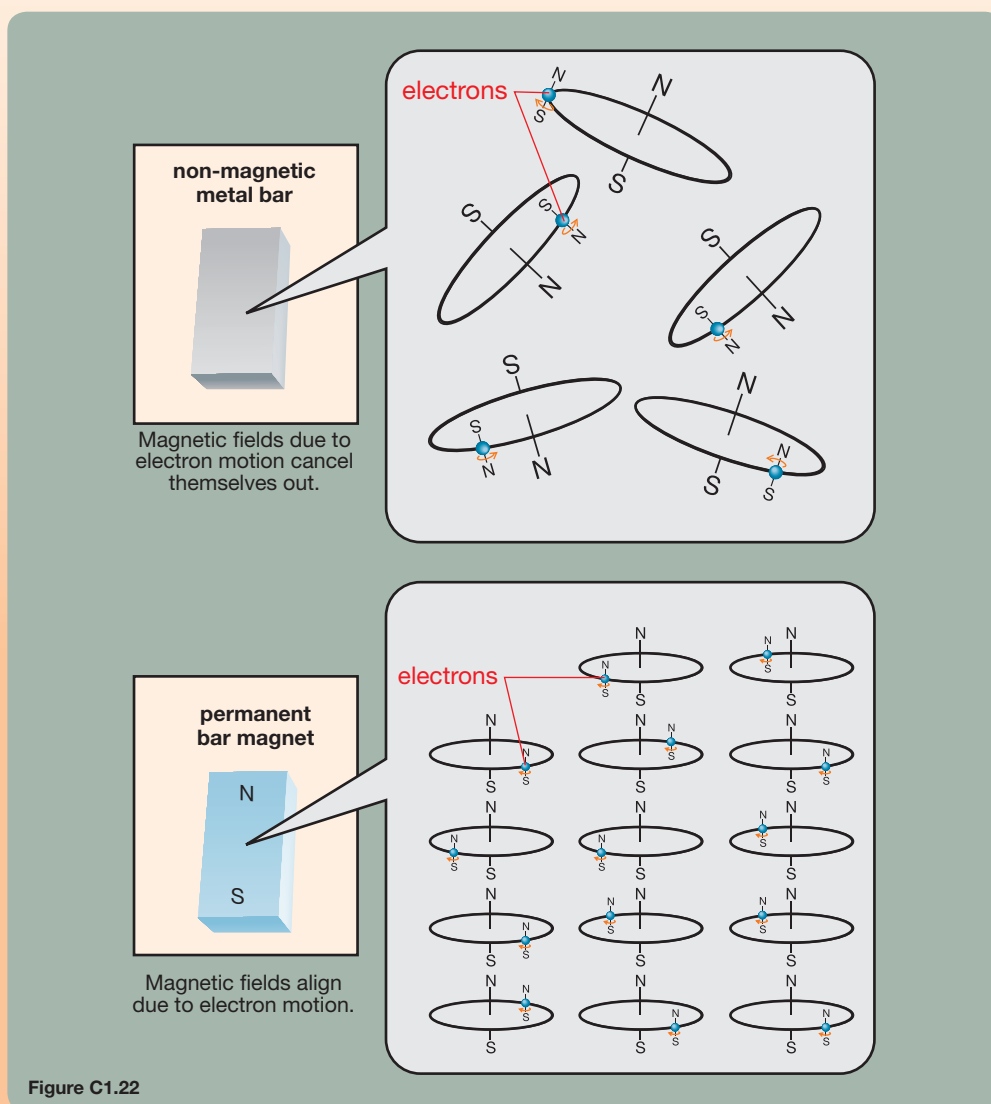
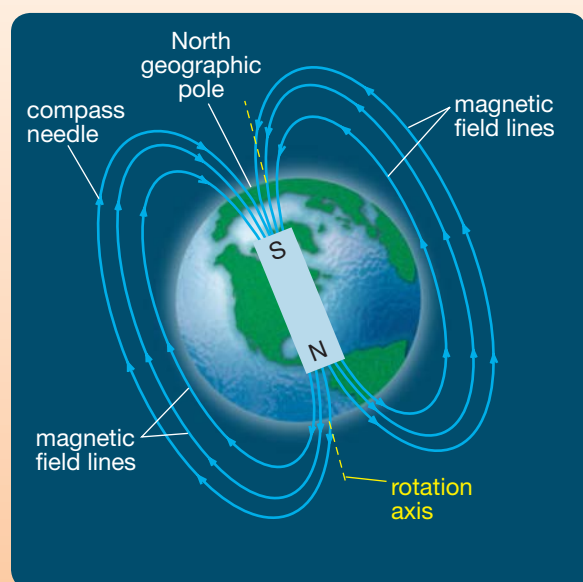
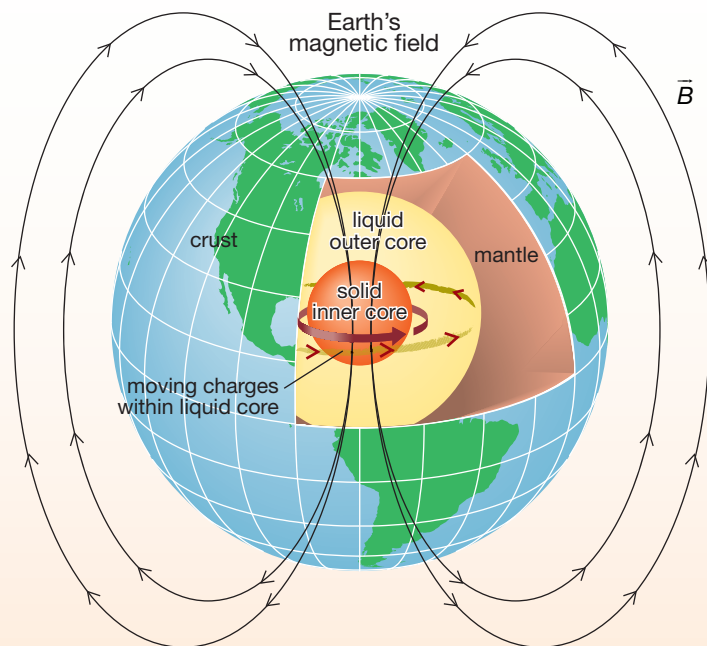


Figure C1.22

Even Earth's magnetic field is a result of moving charges. You will recall from previous courses that deep within the planet is a core of molten material. Although it is not completely understood, many geologists suspect that within the liquid outer portion of Earth's core, matter becomes charged and separated into layers. Since this material is spinning along with everything else comprising the planet, the moving charges form an electric current that generates Earth's magnetic field.



Note that since the north end of a compass needle always points toward the south pole of a magnet, the magnetic south pole of Earth is actually in the northern hemisphere. When people talk about going to the North Pole, they are referring to the geographic North Pole of Earth.

Practice

18. Explain the following statement:

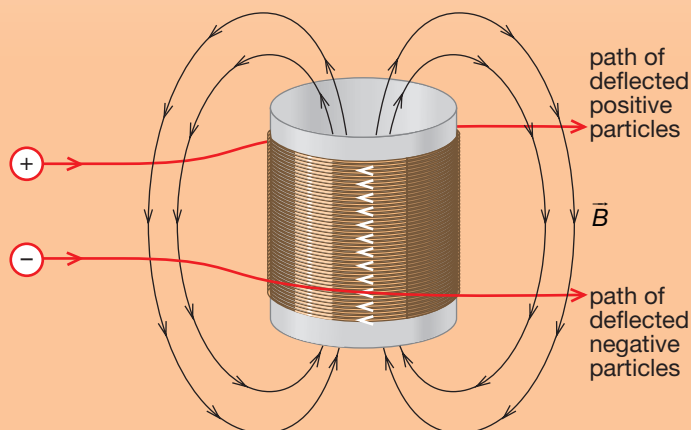
All magnetic fields are generated by moving charges.

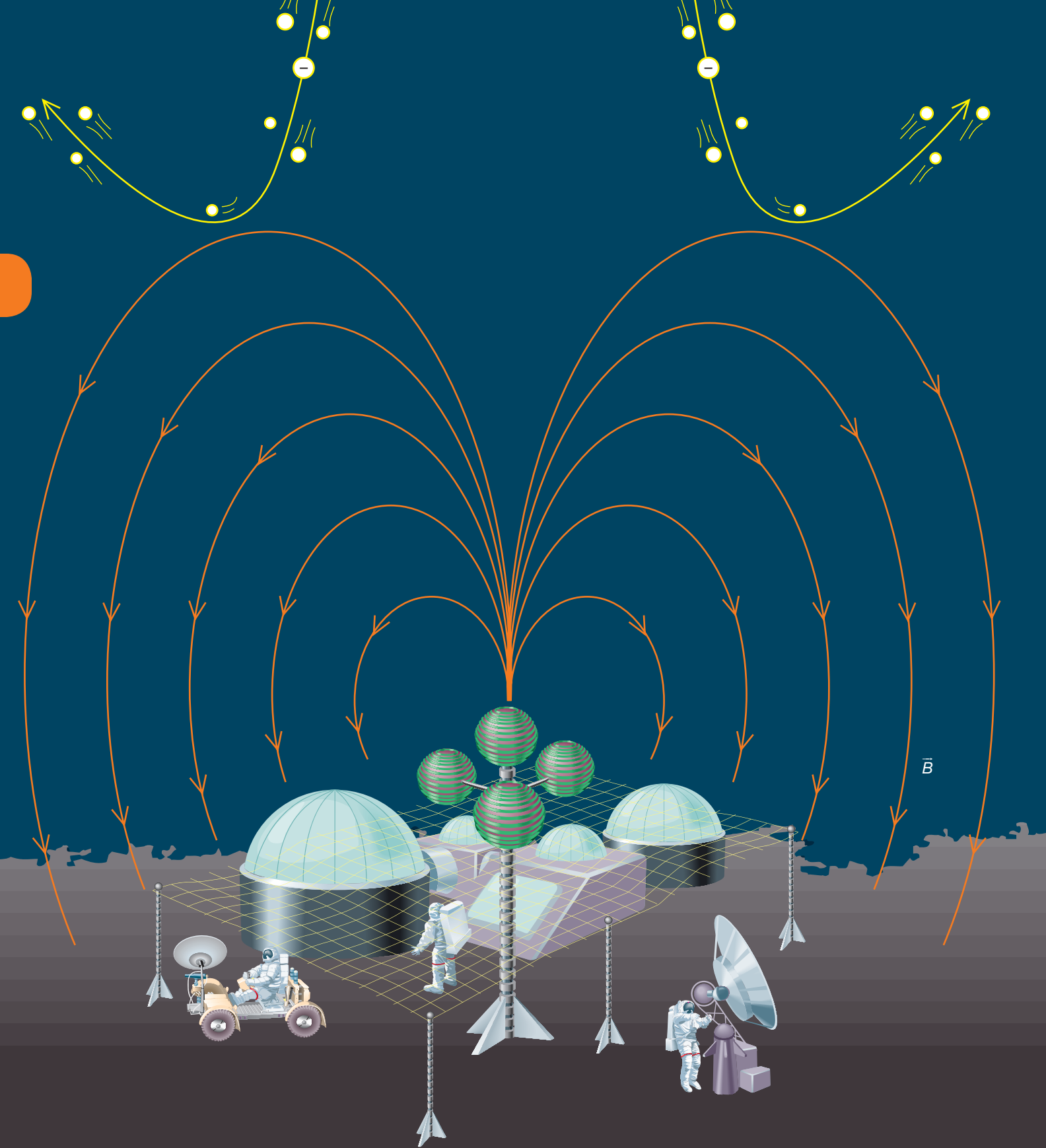
19. Obtain the handout “Labelling the Magnetic Field Around a Current-Carrying Coil” from the Science 30 Textbook CD. Follow the instructions on this handout and supply the missing labels.



Moving Charges Experience Forces in Magnetic Fields

In the “Using a Coil to Deflect an Electron Beam” investigation, you observed the deflection of an electron beam by the magnetic field of a small coil carrying an electric current. This idea is the basis for the design NASA has proposed to protect the moon base from the bombardment of negative particles.





By wrapping the large positive spheres with current-carrying wire, each sphere becomes a large coil. Although the electrons are attracted to the sphere due to the presence of the positive charge, the magnetic field that is generated by the coils is able to deflect the small but fast-moving electrons away from the base.

The positive particles bombarding the Moon's surface would also experience a deflecting force due to the magnetic field. However, because these ions are many thousands of times more massive than electrons, it is more difficult to change the direction of these positive particles using the magnetic field alone—hence the need for the positive charge on the spheres.

NASA's proposal is not without criticism. It has been pointed out that this scheme would be very energy-intensive because the electric current in the coils would have to be very large, and the voltage between the spheres and the lunar surface would likely have to be over 50 000 000 V. If this shielding method is found to be impractical, some other method will have to be used because the hazards associated with prolonged exposure to ionizing radiation are very real.

Just like the Moon, Earth is a massive body travelling through space, and it is exposed to the same sources of radiation: cosmic rays and the solar wind. What protects Earth's inhabitants from these fast-moving particles? You'll be glad to know there are two shields protecting you!

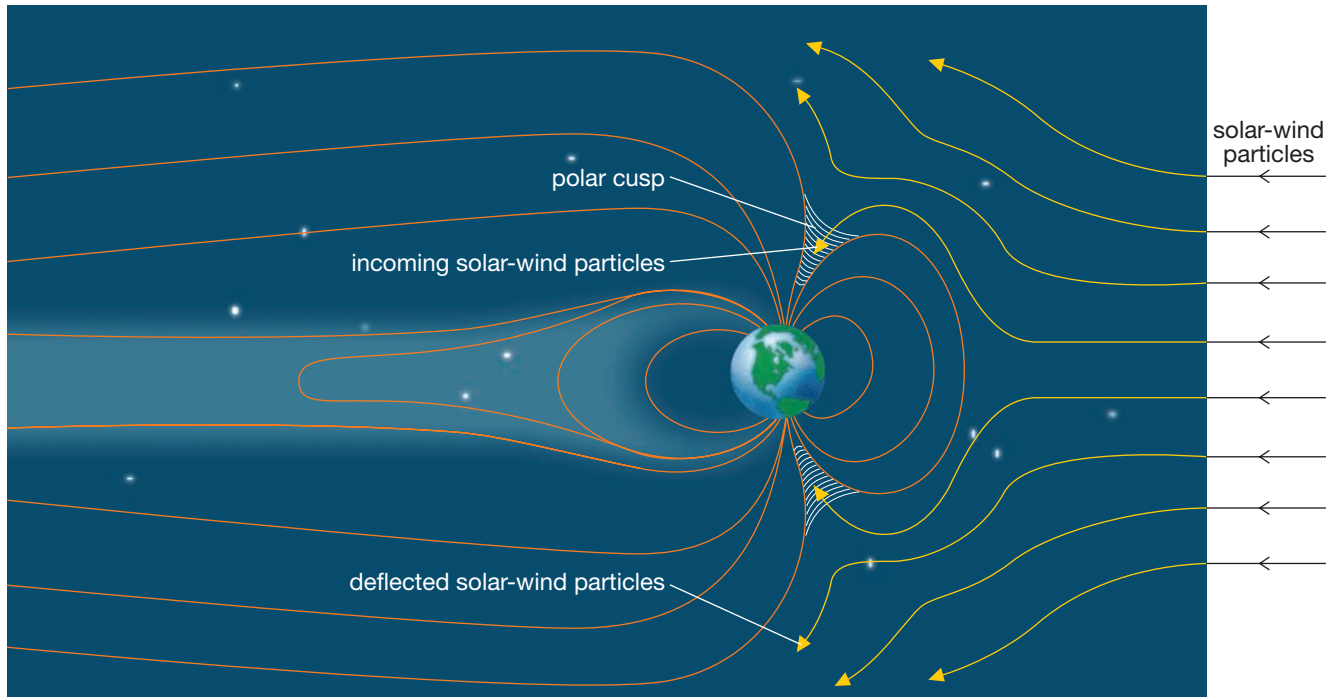


Figure C1.23: Solar-wind particles are deflected around Earth's magnetic field.

The first shield is Earth's magnetic field. It is an effective barrier against about one-third of the cosmic radiation and very nearly all of the solar wind. Note how the solar wind distorts the shape of Earth's magnetic field. As shown in Figure C1.23, most of the solar-wind particles are deflected around Earth's magnetic field. However, there are funnel-like openings called polar cusps that allow some of the solar-wind particles to pass through the magnetic field to the upper atmosphere.

The atmosphere is Earth's second shield. Figure C1.24 shows one of the results of solar-wind particles colliding with the atmosphere—the northern lights. If the collisions involve high-energy electrons with molecular nitrogen, purple light is emitted. Red and green light is emitted from collisions with atomic oxygen. When the solar wind is unusually strong, the charged particles can create giant electric currents in the upper atmosphere. These huge currents create their own magnetic fields. This has powerful effects that can be felt down on Earth—compass needles show incorrect directions and power surges can occur in electrical transmission lines, causing blackouts.

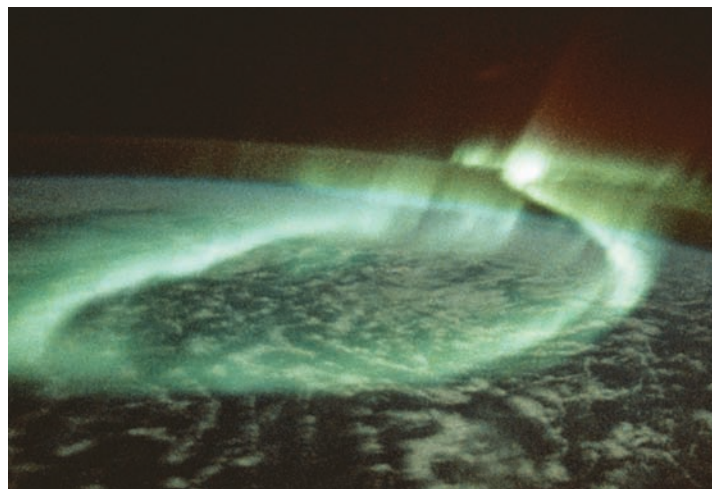


Figure C1.24: The northern lights are the result of solar-wind particles that enter the atmosphere.

The atmosphere is able to absorb the energy from much of the radiation from cosmic rays. A fraction of the cosmic-ray particles are able to penetrate to the planet's surface. There are likely cosmic-ray particles passing through your body as you read this page! These particles are not a cause for alarm, as they form part of the natural background radiation. People who spend a lot of time at very high altitudes, such as the flight crew on a jet airliner, will receive a slightly higher dose of cosmic radiation in their lifetimes than other people because they spend their working days above part of the atmospheric shield. At this time, the health risks associated with this extra exposure to cosmic rays are thought to be minimal.



DID YOU KNOW?

An average person who smokes will receive about 160 times more radiation from the substances in cigarette smoke than they will receive from cosmic radiation.



Practice

20. In this lesson you were introduced to NASA's plans for shielding a moon base with charged spheres wrapped in current-carrying wire. Identify the major challenge engineers will face in making this plan a reality.
21. Identify the two shields that protect Earth's inhabitants from the charged particles of the solar wind and cosmic radiation.

1.2 Summary

The strength of the gravitational field at the surface of Earth, the Moon, or any other object can be calculated using the equation $g = \frac{Gm}{r^2}$, where m is the mass of the source and r is the distance from the centre of the source. The unit for gravitational field strength is newtons per kilogram (N/kg). This serves as a reminder that gravitational field is not the same as gravitational force, which is measured in newtons (N). The equation for gravitational field strength can be combined with the fact that gravitational field lines always point toward the source mass to solve problems where a vector approach is required.

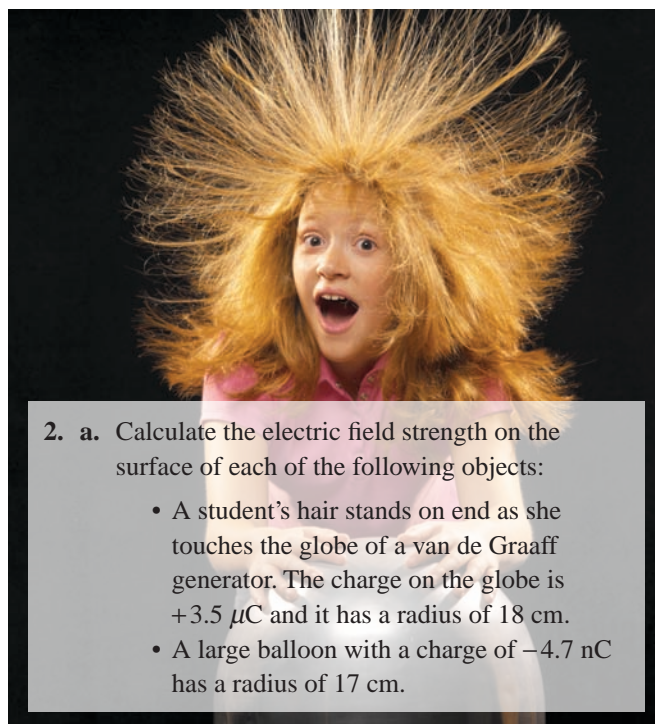
Electric fields are slightly more complicated because the direction of the field lines is determined by the direction of the force on a positive test body. Electric field lines are directed toward negative sources and away from positive sources. Nevertheless, electric field strength can be calculated using the equation $|\vec{E}| = \frac{kq}{r^2}$, where q is the charge on the source and r is the distance from the centre of the source. Once again, units are a very helpful guide to prevent mix-ups between electric field strength, which is measured in newtons per coulomb (N/C), and electric force, which is measured in newtons (N).

The magnetic field is represented by the symbol \vec{B} . No equation for magnetic field is used in Science 30. Unlike gravitational and electric field lines, magnetic field lines form closed loops. In all cases, these looping magnetic fields are established by electric currents. The easiest example of this is a simple coil of current-carrying wire, which surrounds itself with magnetic field lines—setting up one end of the coil as the north pole and one end as the south pole. Electric currents deep within Earth's core are thought to be the source of Earth's magnetic field, which works with the atmosphere to shield the planet from the solar wind and cosmic rays.

1.2 Questions

Knowledge

1. a. Calculate the gravitational field strength on the surface of each of the following objects:
 - Mars has a mass of 6.42×10^{23} kg and an average radius of 3.40×10^3 km.
 - Io, one of Jupiter's moons, has a mass of 8.94×10^{22} kg and an average radius of 1.82×10^3 km.
- b. Sketch diagrams of the gravitational field lines surrounding Mars and Io.
- c. Determine the force of gravity of an astronaut on the surfaces of Mars and Io if the mass of the astronaut is 100 kg.
- d. Identify the key features of each object that account for the differences in your previous answers.



2. a. Calculate the electric field strength on the surface of each of the following objects:
 - A student's hair stands on end as she touches the globe of a van de Graaff generator. The charge on the globe is $+3.5 \mu\text{C}$ and it has a radius of 18 cm.
 - A large balloon with a charge of -4.7 nC has a radius of 17 cm.

- b. Sketch a diagram of the electric field lines around each of the objects.
 - c. A small speck of dust with a charge of $-3.5 \times 10^{-12} \text{ C}$ comes into contact with the surface of each object. Determine the magnitude and the direction of the electric force on the dust speck in each case.
3. All magnetic fields have a similar shape. Draw a simple diagram to illustrate how this statement applies to each of the following sources of magnetic fields.
 - a. a current-carrying coil
 - b. a permanent magnet
 - c. Earth

Applying Concepts

Use the following information to answer questions 4, 5, and 6.

On August 25, 1997, the *Advanced Composition Explorer (ACE)* satellite was launched. *ACE* was designed to monitor the stream of particles from the solar wind and cosmic rays that constantly bombard Earth. From its vantage point at about 1% of the distance between Earth and the Sun, the sensors onboard can provide advanced warning of sudden changes in the flow of charged particles toward Earth. The instant the sensors detect an increase in solar-wind activity, a signal is sent to the United States government's National Oceanic and Atmosphere Administration (NOAA). This organization tracks hurricanes and other large-scale weather events. Some refer to the data from *ACE* as monitoring "space weather." From the moment a warning from *ACE* arrives, the ground teams have about 50 minutes to warn the operators of satellites and electrical power grids.

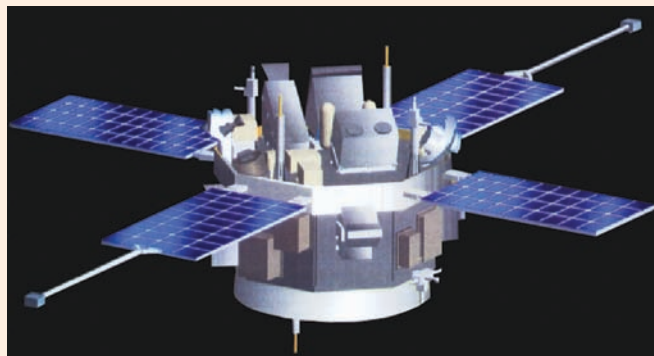
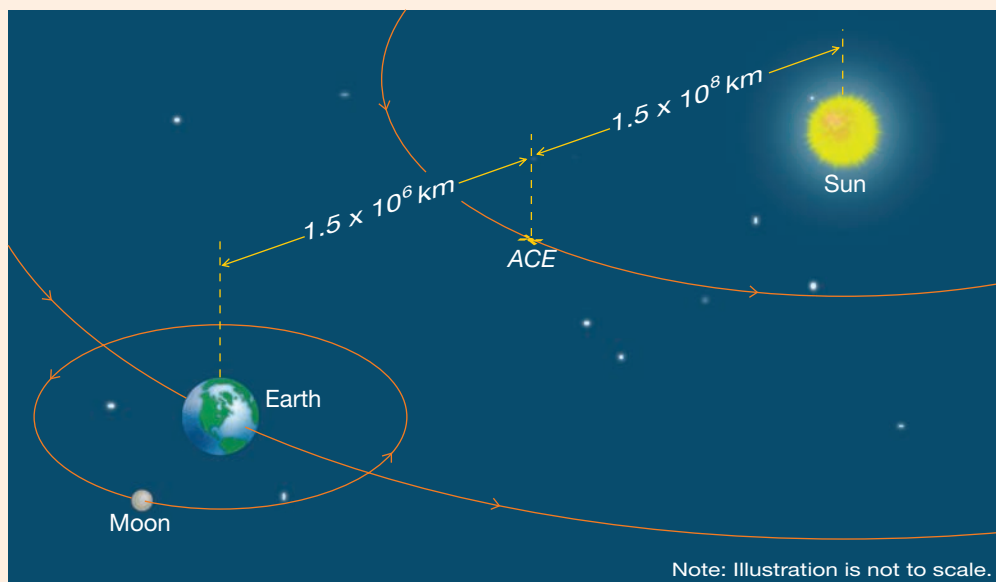


Figure C1.25: NASA's *ACE* satellite



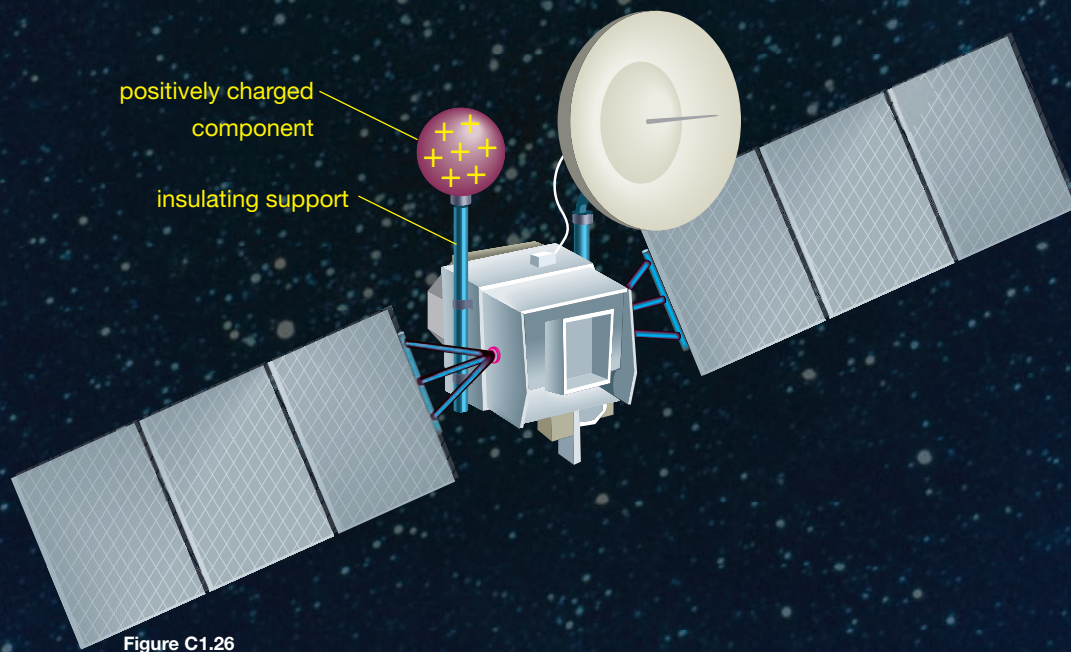
NOAA has given public access to the data from *ACE*. If you enter *ACE Real-Time Solar Wind + NOAA* into a search engine, you can find the NOAA website that displays the current state of the solar wind. If you explore the other links on this site, you can find out more about *ACE* and current research into the solar wind.



4. The location of *ACE* between Earth and the Sun has been precisely chosen so *ACE* will take exactly the same length of time to orbit the Sun as Earth does. This ensures that *ACE* will always be between Earth and the Sun to monitor the solar wind. Normally, objects that are closer to the Sun move faster and complete their orbit around the Sun in less time. The unique location of *ACE* means that the gravitational field of Earth (outward) can act to reduce the gravitational force exerted by the Sun (inward), so the satellite stays aligned with Earth.
 - a. Describe the direction of the gravitational field of the Sun at the location of *ACE*.
 - b. Describe the direction of the gravitational field of Earth at the location of *ACE*.
 - c. Combine your answers to questions 4.a. and 4.b. to explain how the gravitational field of Earth acts to reduce the effects of the gravitational field of the Sun.
5. If *ACE*'s instruments determine that an increase in solar activity is occurring, operators of other commercial satellites will immediately be notified so that they can temporarily "power down" the many electrical devices on the satellites to make them less susceptible to damage.

Figure C1.26 shows a component on a communications satellite that has been charged by high-energy solar-wind particles.

- a. Describe the direction of the electric field lines around this component.
- b. If the electric field becomes strong enough, electrons on nearby components could suddenly move in response, creating a damaging electric current. Determine the direction in which the electrons would flow.
- c. Compare the directions in questions 5.a. and 5.b. Do these answers contradict one another?



6. In places like Fort McMurray, in northern Alberta, several tour companies take people out in the wilderness to view the northern lights. Explain how the information from the *ACE* website could be useful to these groups.